

G. Friction Stir Welding and Processing of Advanced Materials

Principal Investigator: Zhili Feng

Oak Ridge National Laboratory

1 Bethel Valley Road, Oak Ridge, TN 37831

(865) 576-3797; fax: (865) 574-4928; e-mail: fengz@ornl.gov

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Participants:

Michael L. Santella, Oak Ridge National Laboratory

Tsung-Yu Pan, Ford Motor Company

Naiyi Li, Ford Motor Company

Contractor: Oak Ridge National Laboratory

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Objective

- Develop the technological basis for friction stir welding and processing (FSW/P) of advanced high-strength and lightweight materials for the automotive industry.
- Gain fundamental understanding of the relationships between workpiece and tool material properties during FSW/P.
- Characterize the mechanical properties and microstructures of joints.
- Correlate the properties and microstructures produced by FSW/P to the process conditions.

Approach

- Conduct experimental welding and processing tests on advanced materials using the state-of-the-art FSW/P process development system.
- For particular workpiece materials, select the tool material based primarily on high-temperature strength, wear resistance, and chemical compatibility.
- Evaluate mechanical properties and their correlation with microstructures produced by FSW/P.
- Develop predictive modeling capability to study the properties as function of process conditions.

Accomplishments

- Achieved drastic improvements in the fatigue life of FSP cast aluminum alloys.
- Completed a study on FSW of cast magnesium alloy AM60B.
- Conducted FSW tests of high-temperature materials using the tool materials developed at Oak Ridge National Laboratory (ORNL).
- Completed initial development of friction stir spot welding (FSSW) of aluminum alloys.

- Developed an integrated thermal-mechanical-metallurgical model for FSW of aluminum alloy.

Future Direction

- Investigate the effects of heat treatment on the fatigue life of FSP cast aluminum alloys.
 - Carry out FSP of magnesium cast alloy.
 - Explore FSSW of advanced high-strength steels for automotive body structures.
 - Develop new approaches for FSSW without the exit hole for improved structural properties of the joint.
 - Carry out FSSW of other lightweight materials and dissimilar welds.
 - Use transmission electron microscopy to characterize the microstructure improvements to the cast surfaces.
 - Assess the ability of FSP to produce rapidly solidified surface microstructures.
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Introduction

FSW is a relatively new solid state joining method, invented in 1991. The process characteristics and advantages for joining materials that are difficult to join by conventional fusion welding processes were discussed in the 2003 annual report.

Applications of FSW to aluminum alloys have been a great success. Currently, the technology forefronts are rapidly evolving: there is tremendous interest in and efforts to extend the technology to welding high-performance and high-melting-temperature materials. Other novel applications of the process are emerging. For example, it can be used to thermomechanically process a material for microstructure refinement and property improvement.

This program aims at advancing FSW/P technology to promote the increased use and adoption of high-strength lightweight materials in automotive structures, particularly heavy vehicles, to support the goals of the Office of Heavy Vehicle Technology to increase fuel efficiency and reduce emissions of heavy trucks by weight reduction without sacrificing strength and functionality.

FSP Surface Modification of Aluminum Castings

Last year, we began to investigate the application of FSP to modify the microstructures and properties of aluminum alloy castings. Two types of cast alloys were used: A319 (Al-6Si-3.5Cu wt %, nominal) and A356 (Al-7Si-0.3Mg wt %, nominal). Both alloys can be produced as either sand castings or permanent mold castings that are widely used in en-

gine, driveline, and suspension components in a wide variety of automobiles and light trucks. Most of these applications involve dynamic loading, and the primary interest in FSP is for use as a means of improving the durability and reliability of a casting part by locally refining the cast microstructure at critically stressed locations.

Experiments were conducted in collaboration with Ford Research and Advanced Engineering. Testing plates were machined from casting ingots to dimensions of $16 \times 50 \times 200$ mm. FSP was applied on the face of the testing plate to produce an approximately 3-mm-deep processed surface layer. Optical microstructural examination showed that FSP breaks down the coarse dendrites and closes the solidification shrinkage porosity and voids in the original cast microstructure. The resulting refined uniform distribution of eutectic particles increases substantially the static strength and ductility of the FSP region. These results were reported in last year's annual progress report.

This year, the R&D efforts focused on the fatigue life of the FSP material. The procedure to obtain the fatigue life test specimen was the same as in last year's static mechanical property test. A sub-sized tensile fatigue specimen with gage dimensions of $2 \times 2 \times 15$ mm was then cut from the processed material. The testing gage length is entirely within the processed region and transverse to the FSP bead, as shown in Figure 1.

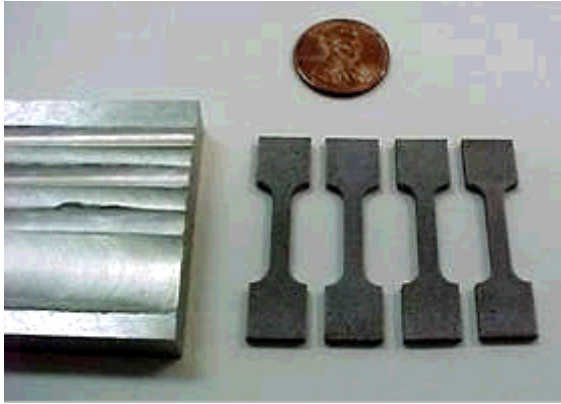


Figure 1. Tensile specimens used for fatigue life testing of FSP aluminum castings.

Tables 1 and 2 show fatigue life testing results for A356 and A319 cast alloys, respectively. It is evident that the FSP material showed drastic improvement in fatigue life, compared with the as-cast material, for both cast alloys. The increase in fatigue life can be attributed to the substantial strength and ductility improvements and the elimination of solidification shrinkage porosity (crack initiation sites) associated with the thermo-mechanical processing of cast microstructures during FSP.

Table 1. Fatigue testing results for A356 cast aluminum alloy

Condition	Applied strain	Stress amplitude, ksi @ ½ life	Neuber stress range ksi @ ½ life	Life, # of reversals
As-cast	2.0×10^{-3}	15.5	39.0	7,700
FS processed	2.0×10^{-3}	19.4	43.9	93,848

Table 2. Fatigue testing results for A319 cast aluminum alloy

Condition	Applied strain	Stress amplitude, ksi @ ½ life	Neuber stress range ksi @ ½ life	Life, # of reversals
As-cast	1.4×10^{-3}	13.4	29.0	100,980
FS processed	1.5×10^{-3}	18.0	39.0	281,442

The findings from this program show that FSP has potential as a very effective process to locally modify cast microstructures at critical locations to improve the overall durability of the component. This would open new opportunities to support wider use of aluminum castings in vehicles, which could directly impact weight reduction. We plan to conduct more comprehensive study on this subject in the future phases of this program.

FSW of Cast Magnesium Alloy

The use of magnesium has grown considerably in the past 10 years and continues to rise in the automotive industry. This increase is mainly attributed to the lightness of magnesium—it is one-third lighter than aluminum and four-fifths lighter than steel. Magnesium also has the highest strength-to-weight ratio among the commonly used metals. Moreover, it has many other advantages, e.g., good

castability, high die casting rates, electromagnetic interference shielding properties, parts consolidation, dimensional accuracy, and excellent machinability. With these characteristics, magnesium provides opportunities for the automotive industry, in which weight reduction, fuel economy, and environmental friendliness of vehicles are increasingly demanded.

Despite its good castability, it is not always possible or economically viable to cast complex magnesium parts. Joining of the same or different types of magnesium alloys, as well as joining magnesium to other materials, is essential to enable the economical manufacturing of complex parts and structures.

An increasing number of magnesium components for automotive applications are fabricated by high-pressure die-cast process. This type of magnesium casting has limited ductility, contains gas occlusions, and is generally difficult to weld satisfactorily by fusion welding techniques.

In this part of the program, we conducted a study on FSW of AM60B, an Mg-Al-Mn cast alloy under development for automotive applications. The experiments were conducted in collaboration with the Research and Advanced Engineering Lab of Ford Motor Company.

The AM60B cast plates were produced by the high-pressure die casting process. The nominal dimensions of the casting plate were $127 \times 25.4 \times 6$ mm. Two die-cast plates were FSW butt-welded along their long dimensions, as shown in Figure 2. In consideration of the typical automotive production environment, all welds were made without any special cleaning of the as-cast surface. In other words, the welds were made under the as-cast surface condition. In addition, no shielding gas was used during welding.

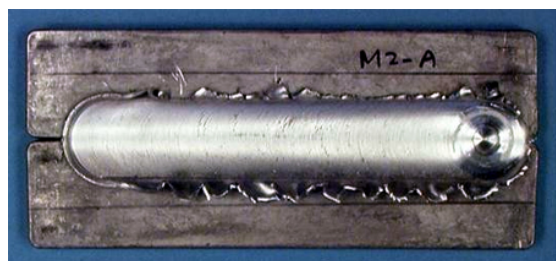


Figure 2. A friction-stir butt weld between two casting plates (450 rpm).

FSW was conducted using the FSW process development system acquired by ORNL with funding support from the HSWR Materials Program and other DOE programs. The machine is capable of simultaneous force-controlled or displacement-controlled operation of three independent axes with adjustable, adaptable pin tools for on-the-fly mode switching between fixed, adjustable, and self-reacting welding modes. It also handles computer-controlled operation and key process parameter monitoring and is capable of making non-linear, variable-thickness, and double-curvature welds.

The FSW tool was made of H13 tool steel. The shoulder diameter was 0.75 in. (19 mm), and the threaded pin was 0.25 in. (6.35 mm) in diameter. The length of the pin was 0.185 in. (4.7 mm), slightly shorter than the thickness of the plates. Two rotating speeds were used in this study, 375 and 450 rpm. The linear welding speed was kept at 152.4 mm/min. No elaborate attempt was conducted

to optimize the process conditions in this phase of the study.

The optical macroscopic photo in Figure 3 shows the cross-section of the weld joint. The gas pores were clearly visible in the base metal as a result of the high gas content in the high-pressure die casting process. In the stir zone, the pores were significantly reduced on one side of the weld but still visible in the other side, which is characteristic of all the welds examined in this study.

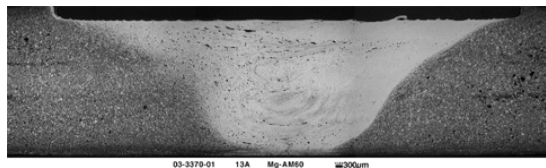


Figure 3. Transverse section of a friction stir weld of AM60B.

To determine the strength of the welded joint, tensile testing samples were machined out from the middle of the specimen, as shown in Figure 4, and prepared in accordance with ASTM B557 specifications. Tensile properties of the base metal were also determined for comparison.

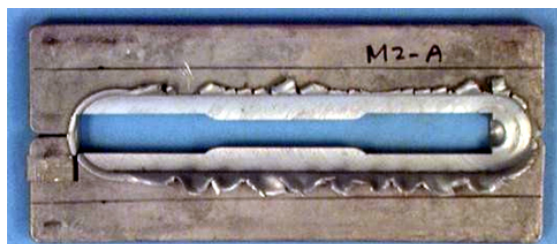


Figure 4. Longitudinal tensile sample per ASTM B557 sub-size specimen.

The tensile testing results are presented in Figure 5 and 6. The weld made under the low-rpm condition (M1) maintains the ultimate strength of the base metal but doubles the ductility. The high-rpm condition (M2) slightly lowers the weld tensile strength but still offers significant improvement in ductility.

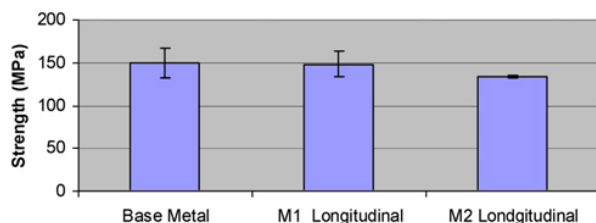


Figure 5. Longitudinal tensile strength of FSW alloy AM60B.

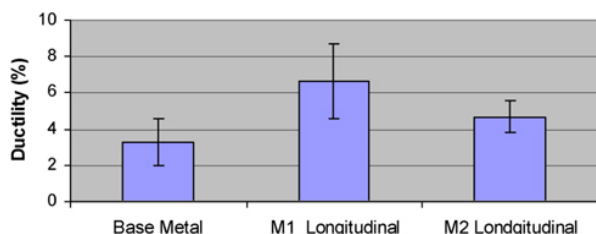


Figure 6. Longitudinal ductility of FSW alloy AM60B.

FSW of High-Temperature Materials

In 2003, tool material design activities at ORNL led to the development of two new alloys for use as tool materials for FSW/P of high-temperature materials. In 2004, we conducted initial welding trials using the new tool materials developed by ORNL. Welds were successfully made for the following alloys: mild steel, stainless steel 304, CP Ti, and Ti-6Al-4V.

Initial testing showed that the ORNL tool materials exhibit minimal tool wear and deformation. The tungsten-based tool material has excellent toughness over the temperature range from the ambient to at least 1500°C. The tool material was very forgiving of unexpected sudden temperature and load changes during the welding trials, which would have led to premature failure of other tool materials under similar situations. Additional evaluations of the performance of the tool material, as well as the microstructure and properties of the friction stir welds of high-temperature materials, are currently under way.

Figure 7 shows the tungsten-based and irridium-based tool materials developed at ORNL. Figure 8 shows the process in action in welding stainless steel 304. Figure 9 shows two examples of high-temperature friction stir welds made with ORNL's tungsten-based tool material.



Figure 7. Two development-grade FSW tool materials developed at ORNL.

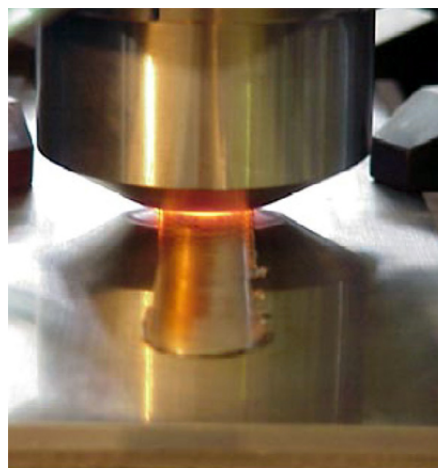


Figure 8. FSW of stainless steel.

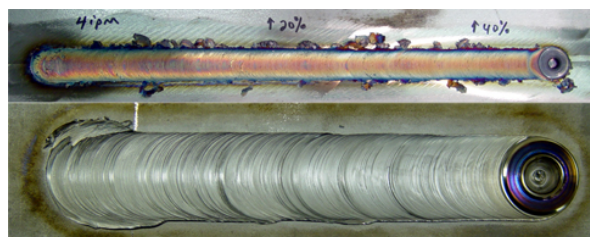


Figure 9. Sample welds made with ORNL tool material. Above: stainless steel 304, below: Ti-6Al-4V. Plate thickness: 0.25 in. (6.35 mm).

FSW of Aluminum Alloys

FSSW, or spot friction welding, is a new welding process invented by Mazda in 1993. It has been a subject of great interest for the U.S. automotive industry because of its process simplicity, low capital investment cost, and significant energy savings (up to 99% in the case of aluminum welding), compared with conventional resistance spot welding.

We are collaborating with Ford to further advance the technology for the U.S. automotive industry.

FSSW creates a spot lap-weld without bulk melting. The principles of the process are schematically illustrated in Figure 10. Similar to linear FSW, FSSW uses a cylindrical tool with a co-axial protruded pin. The welding cycle begins when the pin plunges into the upper sheet of the lap joint. The plunge load is supported from the bottom side with a backing plate or anvil to sustain the plunging load. The heat generated by the rotating pin softens the material and facilitates the penetration of the pin. Much more heat is generated to further soften a large region of the material underneath the tool shoulder after the tool shoulder contacts the top surface of the upper sheet. The softened material is pushed and stirred to form the metallurgical bond around the rotating pin. The forge pressure from the tool shoulder also keeps the interface between the two workpieces in intimate contact to facilitate the bonding. The tool is retracted at the end, leaving the characteristic hole in the middle of the weld.

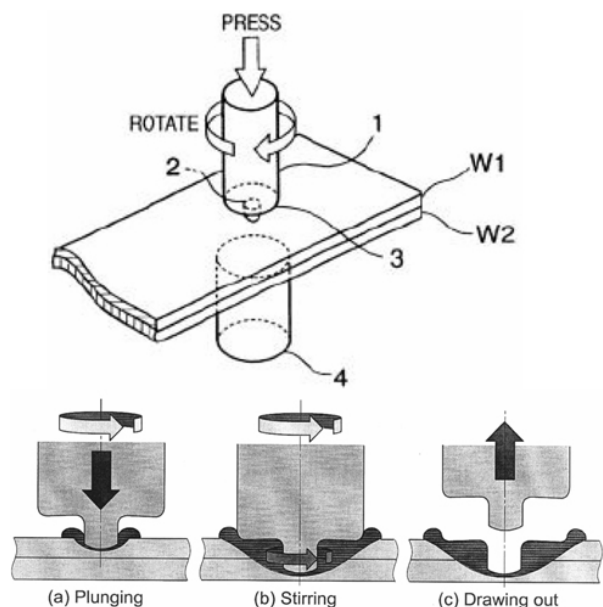


Figure 10. Principles of FSSW with fixed pin.

Currently, FSSW is load controlled. This study was to develop a displacement-controlled operation mode that is more suitable for a high-volume production environment.

Figure 11 illustrates schematically the basic operation of a displacement-controlled FSSW process. After the tool starts rotating, it is driven into the sample at a controlled plunging rate to reach a pre-determined depth. The process then stops and the tool retracts. The normal force, recorded as an output, increases to a relatively low plateau when the pin initially plunges into the material. It then increases to a higher value when the shoulder of the tool touches the sample.

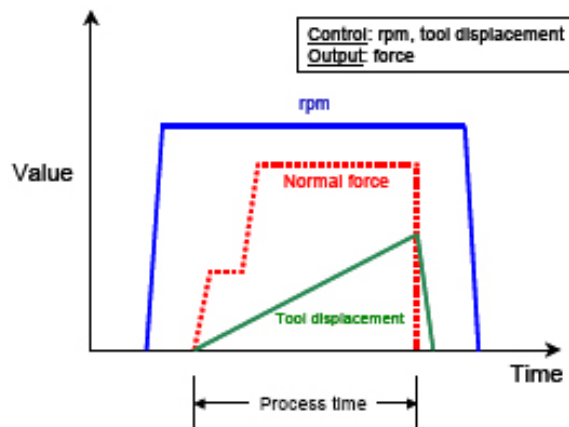


Figure 11. Schematic diagram of a displacement controlled FSSW operation.

The experiments were carried out on ORNL's FSW process development system. Specimens of aluminum alloy 6111-T4, 25.4 mm in width, 101.6 mm in length, and 0.94 mm in thickness were used. The standard overlapping distance of 25.4 mm was adopted. The weld was made at the center of the overlapping region. The spot weld was made at 2000 rpm. The tool plunging displacement was set at between 1.6 and 1.9 mm.

Figure 12 shows the lap shear tensile results of samples made between 1.6 and 1.9 mm in depth. Each data point represents an average of at least three samples. Initially the joint strength increased with the plunge depth. It reached a maximum value and then dropped off as plunge depths were further increased. The maximum lap-shear strength exceeded 3 kN at about 1.8 mm plunge depth. It is important to note that the tensile strength obtained in our study generally exceeded these reported with the load controlled operation.

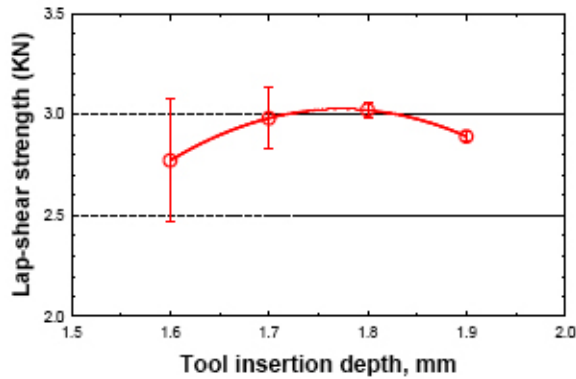


Figure 12. Lap-shear strength of spot friction welded 6111-T4 samples at different insertion depths by displacement control welding.

Figure 13 shows a micrograph of the cross-section of a sample with a plunge depth of 1.7 mm. Figure 14 (a) and (b) show the microstructures in the parent material region and stirred zone, respectively. The refinement of grain size in the stirred zone is obvious: it is about 3–5 times smaller compared with the grains in the parent material.

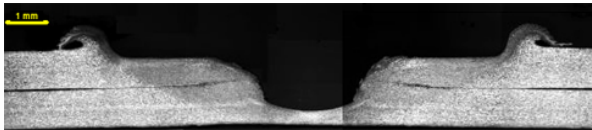


Figure 13. Macro cross-section of a spot friction stir weld of Al611-T6.

Modeling of FSW

As with many other welding processes, residual stresses are expected in a friction stir weld. The welding thermal cycle also introduces microstructural changes in the weld region of many high-performance engineering materials. The resultant property and residual stress fields in a friction stir weld joint often govern the mechanical strength of the welded structures. For automobile structures, this affects both the durability of the vehicle in service and the formability of the welded part during post-welding forming and stamping operations.

An integrated thermal-mechanical-metallurgical model was used to study the residual stress field and the spatial property gradient in an Al6061-T6 friction stir weld. The simulations were conducted using a 3-dimensional model, accounting for the frictional heating, aging, and dissolution processes

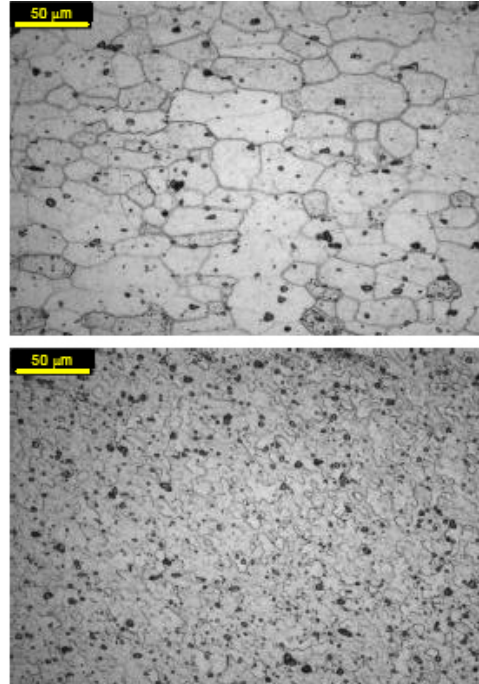


Figure 14. Micrograph of the base metal (top) and stir zone (bottom) of SFW 6111-T4.

of the precipitates and the mechanical contact of the moving tool.

Temperature-dependent material properties were used in the simulation. In addition, the residual stress fields were measured using the neutron diffraction mapping technique to validate the model predictions.

The integrated model enables high-fidelity simulations of the thermal, mechanical, and metallurgical changes during the FSW process and the resulting microstructure, property, and residual stress inhomogeneity in the weld region. This type of model would make it possible to effectively interrogate the influence of various aspects of the process (process parameters, material, and geometry) on the performance of a friction stir weld under different post-welding fabrication conditions (such as stamping and forming) and in-service loading conditions. As an example, Figure 15 shows simulation results for temperature, hardness, and residual stress fields in the weld, and their combined effects on the deformation and failure behavior of an aluminum alloy Al6061-T6 friction stir weld in the tensile test.

For the friction stir welds investigated, it was found that the residual stress distribution is strongly

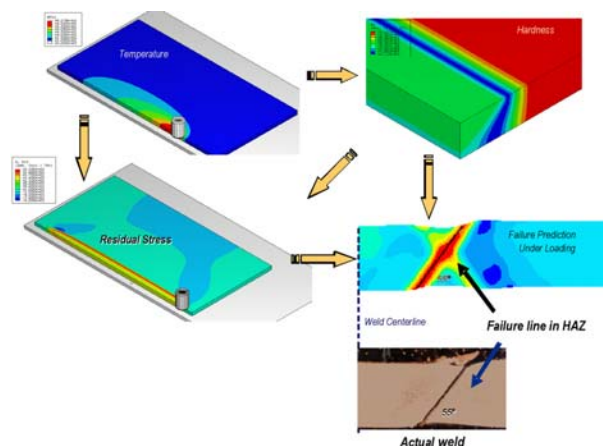


Figure 15. Integrated thermal-mechanical-metallurgical friction stir welding simulations provide insights into the performance of welded structures.

dependent on the welding process parameters and the degree of material softening during welding. The failure of a friction stir weld under tensile load is controlled by a combination of material softening and the high residual stresses in the heat-affected zone.

Conclusions

This program has made considerable progress in FY 2004 in advancing the FSW/P technology: FSP of cast aluminum alloys resulted in drastic micro-

structure and property improvement. A cast magnesium alloy was friction stir welded. FSW of high-temperature materials was explored, as well as FSSW of aluminum alloy. Integrated modeling was used to study the property and residual stresses and their effects on the performance of aluminum weld structures.

Publications

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